

formed of only an intrinsic 2D material in which neither gas nor impurities are adsorbed on a surface thereof. For example, the first 2D material layer may be a portion of the 2D material layer **14**, which is formed in a vacuum state at a significant level (e.g.,  $10^{-6}$  Torr or less) and covered with the passivation layer **18** before being exposed to air. On the other hand, the 2D material layer **14** in the second region **14b** (hereinafter also referred to as a 'second 2D material layer') is a layer in a state in which oxygen ( $O_2$ ) is adsorbed on a surface of a 2D material layer (in the exemplary embodiments, although the adsorbed oxygen ( $O_2$ ) is illustrated slightly exaggerated in the drawing, this is only schematically illustrated for convenience of explanation and understanding). In the exemplary embodiments, a portion such as the second 2D material layer in which oxygen is adsorbed on a surface thereof is referred to as 'an oxygen adsorption material layer.' Since a diode including the above 2D material layer **14** has a simple structure and a semiconductor layer is formed of a single 2D material, there is no interface issue.

**[0052]** The 2D material which forms such a 2D material layer **14** may be a metal chalcogenide-based material. For example, at least one of metal chalcogenide-based materials may include one transition metal of Mo, W, Nb, V, Ta, Ti, Zr, Hf, Tc, and Re and one chalcogen element of S, Se, and Te, and may be a transition metal chalcogenide material represented by  $MX_2$  (Here, M denotes a transition metal and X denotes a chalcogen element). Accordingly, the transition metal chalcogenide material may be, for example,  $MoS_2$ ,  $MoSe_2$ ,  $MoTe_2$ ,  $WS_2$ ,  $WSe_2$ ,  $WTe_2$ ,  $ZrS_2$ ,  $ZrSe_2$ ,  $HfS_2$ ,  $HfSe_2$ ,  $NbSe_2$ ,  $ReSe_2$ , etc. Alternatively, a transition metal chalcogenide-based material may not be represented by  $MX_2$ , and a compound (a transition metal chalcogenide material) of a transition metal of Cu and a chalcogen element of S may be expressed as, for example, CuS. Since the CuS may also be the 2D material, the CuS may be applied as a transition metal chalcogenide-based material.

**[0053]** As another example, the metal chalcogenide-based material may be a non-transition metal chalcogenide material including a non-transition metal. The non-transition metal may be, for example, Ga, In, Sn, Ge, Pb, etc. That is, a compound of a non-transition metal such as Ga, In, Sn, Ge, Pb, etc. and a chalcogen element such as S, Se, and Te may be used as a non-transition metal chalcogenide-based material. Accordingly, the non-transition metal chalcogenide material may be, for example,  $SnSe_2$ , GaS, GaSe, GaTe, GeSe,  $In_2Se_3$ ,  $InSnS_2$ , etc.

**[0054]** According to an exemplary embodiment, types of 2D materials which form the first 2D material layer and the second 2D material layer are the same. That is, both the first and second 2D material layers **14a** and **14b** are formed of the same 2D material. The 2D material layer **14** may be a material having a "semiconductor" characteristic. For example, the 2D material layer **14**, more specifically, the first 2D material layer in which oxygen is not adsorbed on a surface thereof, may be a P-type semiconductor or an N-type semiconductor. The second 2D material layer which is an oxygen adsorption material layer may be an N-type semiconductor or a P-type semiconductor, the opposite of the first 2D material layer.

**[0055]** To this end, the 2D material layer **14** may be formed of a material having a characteristic in which a difference between a work function when oxygen is adsorbed on a surface thereof and a work function when the

oxygen is not adsorbed on the surface thereof is greater than or equal to a predetermined value. That is, the 2D material layer **14** may be formed of a material having a characteristic in which a work function is changed to a predetermined value or more when oxygen is adsorbed on a surface thereof. According to an exemplary embodiment, the predetermined value may be changed according to an electrical characteristic required for a semiconductor device. For example, when the semiconductor device is a diode, the 2D material layer **14** may be formed of a 2D material having a characteristic in which a difference between a work function of the second 2D material layer and a work function of the first 2D material layer is 0.3 eV or more. For cases in which a change in the work function of the 2D material layer **14** is caused by the adsorption of oxygen, it should be apparent to those skilled in the art that the present exemplary embodiment may be applied in cases of a positive change as well as a negative change.

**[0056]** According to an exemplary embodiment, the 2D material layer **14** may be formed of  $MoS_2$  which is one of the transition metal chalcogenide materials. According to an exemplary embodiment,  $MoS_2$  is a representative example of the 2D material in which a value of a work function is changed by adsorbing oxygen on a surface thereof. As described below, the value of the work function of  $MoS_2$  is restored to an original value by separating the adsorbed oxygen. That is, the work function of  $MoS_2$  has a reversible characteristic according to adsorbing and separating the oxygen. Hereinafter, a detailed physical characteristic of the 2D material layer **14** formed of  $MoS_2$  will be described in detail with reference to experimental results.

**[0057]** FIG. 2A is a graph illustrating a change in a work function of  $MoS_2$  according to a surrounding environment. The change in the work function illustrated in FIG. 2A is a result in which a single-layered  $MoS_2$  is formed on a P-type silicon substrate and then the work function of  $MoS_2$  is electrically measured using a Kelvin probe including a tip having a 3 mm diameter. The Kelvin probe may measure a work function in-situ for each pressure (in an atmospheric environment (ambient) or in a high vacuum) or for each gas atmosphere in a set-up.

**[0058]** Referring to FIG. 2A, the work function of  $MoS_2$  was measured to be about 4.36 eV in an atmospheric environment (a time in a range of 0 to 7 minutes). When an inside of a chamber of the Kelvin probe is changed to a high vacuum state (about  $10^{-9}$  Torr) by pumping out the air included in the inside of the chamber, the work function became about 4.1 eV (a time in a range of 8 to 90 minutes). When an annealing process is performed at a temperature of about 400° C. for about 2 hours, the work function becomes about 4.35 eV again and was restored to an initial state (a time in a range of 90 to 221 minutes). Subsequently, when oxygen ( $O_2$ ) is injected into the inside of the chamber, the work function is increased to 4.53 eV (a time of 290 minutes or more).

**[0059]** Accordingly, it can be seen that the work function of  $MoS_2$  in air becomes about 4.36 eV, and about 4.1 eV in a high vacuum state. Also, it can be seen that the value of the work function of  $MoS_2$  is restored to an original value when oxygen is adsorbed again in a high vacuum state, and as an amount of the adsorbed oxygen is increased by increasing a concentration of oxygen in a surrounding environment, the work function of  $MoS_2$  is increased to about 4.53 eV. Also, it can be seen that a main factor in changing the work